

## TOTAL AND EXTREME PRECIPITATION CHANGES OVER THE NORTHEASTERN UNITED STATES

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34     **Abstract**

35     The Northeastern United States has experienced a large increase in precipitation over recent  
36     decades. Annual and seasonal changes of total and extreme precipitation from station  
37     observations in the Northeast are assessed over multiple time periods spanning 1901–2014.  
38     Spatially averaged, both annual total and extreme precipitation across the Northeast have  
39     increased significantly since 1901, with changepoints occurring in 2002 and 1996, respectively.  
40     Annual extreme precipitation has experienced a larger increase than total precipitation; extreme  
41     precipitation from 1996–2014 was 53% higher than from 1901–1995. Spatially, coastal areas  
42     received more total and extreme precipitation on average, but increases across the changepoints  
43     are distributed fairly uniformly across the domain. Increases in annual total precipitation across  
44     the 2002 changepoint have been driven by significant total precipitation increases in fall and  
45     summer, while increases in annual extreme precipitation across the 1996 changepoint have been  
46     driven by significant extreme precipitation increases in fall and spring. The ability of gridded  
47     observed and reanalysis precipitation data to reproduce station observations was also evaluated.  
48     Gridded observations perform well in reproducing averages and trends of annual and seasonal  
49     total precipitation, but extreme precipitation trends show significantly different spatial and  
50     domain-averaged trends than station data. North American Regional Reanalysis generally  
51     underestimates annual and seasonal total and extreme precipitation means and trends relative to  
52     station observations, and also shows substantial differences in the spatial pattern of total and  
53     extreme precipitation trends within the Northeast.

54

55     **1 Introduction**

56 Multiple studies have found increasing total and extreme precipitation across the Northeastern  
57 United States (Kunkel et al. 2013a; Peterson et al. 2013; Hayhoe et al. 2007), and extreme  
58 precipitation events have increased faster over the Northeast region than in any other part of the  
59 United States (Kunkel et al. 2013a). Hayhoe et al. (2007) found an increase of 10 mm decade<sup>-1</sup> in  
60 annual total precipitation from 1900 to 1999 using the 93 stations in the U.S. Historical  
61 Climatology Network in the states of Maine, New Hampshire, Vermont, Massachusetts, Rhode  
62 Island, Connecticut, New York, New Jersey, and Pennsylvania. Using the U.S. Climate  
63 Divisional Dataset Version 2 over the domain of Hayhoe et al. (2007) plus Maryland, Delaware,  
64 West Virginia, and Washington D.C., Kunkel et al. (2013b) found a 10.2 mm decade<sup>-1</sup> increase  
65 in annual total precipitation over 1895–2011. However, across a similar time period (1901–2000)  
66 as Hayhoe et al. (2007), Walsh et al. (2014) and Kunkel et al. (2013b) found a trend of  
67 approximately 5.6 mm decade<sup>-1</sup>.

68

69 Extreme precipitation events have also been increasing across the Northeast, both in intensity  
70 and frequency, particularly over the past three decades (Walsh et al. 2014; Kunkel et al. 2013a;  
71 Hoerling et al. 2016). This increase in extreme precipitation events is consistent with expected  
72 impacts of climate change on precipitation, primarily more extreme events driven by the ability  
73 of the atmosphere to hold more water as described by the Clausius-Clapeyron relationship (e.g.,  
74 Trenberth 1998; Mishra et al. 2012; Prein et al. 2017). Kunkel et al. (2013a) found significant  
75 increases in both 1-in-5-year 2-day precipitation events and the amount of precipitation falling  
76 on the 1% wettest days during the time period 1957–2010 for the Northeast. Hoerling et al.  
77 (2016) discovered a 2–3% increase per decade in both the total amount and frequency of heavy  
78 precipitation events (5% wettest days) in the Northeast over 1901–2013, with the increases in

79 heavy precipitation total amount, frequency, and intensity accelerating after 1979. Walsh et al.  
80 (2014) also evaluated trends in the amount of precipitation falling in the Northeast on the 1%  
81 wettest days using the Global Historical Climatology Network-Daily dataset, finding a striking  
82 increase of 71% from 1958 to 2012.

83

84 Given the growing consensus on the recent dramatic increase of extreme precipitation across the  
85 Northeast, our motivation is to explore the temporal and spatial attributes of precipitation  
86 increases in greater detail, as well as assess the ability of gridded observational and reanalysis  
87 datasets to capture this precipitation increase. Specifically, we add to this literature by: 1.  
88 assessing the sensitivity of total and extreme precipitation changes to the time period of analysis  
89 (Sections 3.1.1, 3.1.3), 2. exploring the spatial distribution of total and extreme precipitation  
90 across the Northeast (Sections 3.1.2, 3.1.4), 3. analyzing seasonal contributions to changes in  
91 annual total and extreme precipitation (Sections 3.1.5), and 4. evaluating the consistency of  
92 means and trends in precipitation across station, gridded, and reanalysis data (Section 3.2).

93

94 **2 Data and Methods**

95 We define the Northeast as Maine, New Hampshire, Vermont, Massachusetts, Connecticut,  
96 Rhode Island, New Jersey, New York, Pennsylvania, Maryland, Washington D.C., Delaware,  
97 and West Virginia. This domain was selected for consistency with Walsh et al. (2014). This  
98 study focuses on precipitation changes recorded by station observations since 1901, which are  
99 variable in length by station, as well as gridded and reanalysis data spanning 1915–2011 and  
100 1979–2014, respectively. We therefore conduct our analyses for three time periods: 1901–2014,  
101 1915–2011, 1979–2014. To facilitate intercomparisons among the three datasets, an additional

102 period, 1979–2011, is also analyzed. Each of the three datasets used – station observations,  
103 gridded observations, and reanalysis – as well as the metrics and processes used to analyze them,  
104 are described below.

105

## 106 2.1 Climate Data

107 Station observations were derived from the Global Historical Climatology Network-Daily  
108 (GHCN-D) dataset (Menne et al. 2012a, b), which is produced and archived by the National  
109 Oceanic and Atmospheric Association (NOAA) National Climatic Data Center. GHCN-D has  
110 been used extensively in climate analysis and monitoring studies that require daily data, such as  
111 assessments of heavy rainfall events, heat waves and cold snaps, and is the official archive for  
112 US daily data (Menne et al. 2012b; Peterson et al. 2013). It consists of over 96,000 stations  
113 worldwide that capture all or a subset of: daily maximum and minimum temperature,  
114 precipitation, snowfall, and snow depth. The time period of record varies by station from less  
115 than one year to 177 years, with the average precipitation record spanning 33.1 years (Menne et  
116 al. 2012b).

117

118 Because the temporal coverage of GHCN-D varies, we first extracted all 5,867 stations for the  
119 Northeast domain as defined above and then selected stations based on an 80% completeness  
120 threshold (Alexander et al. 2006; Xie et al. 2007; Higgins et al. 2007). We first require that each  
121 year be at least 80% complete and treated years with less than 80% complete records as missing  
122 values in order to minimize the potential influence of years with seasonal gaps. Then, we  
123 selected stations with daily records at least 80% complete in one or two periods (1901–2014:

124 80% complete overall and 80% complete from 1979–2014; 1915–2011: 80% complete from  
125 1915–2011 and 80% complete from 1979–2011; 1979–2014: 80% complete from 1979–2014;  
126 1979–2011: 80% complete from 1979–2011). Applying these standards yields 116 qualifying  
127 stations for the 1901–2014 period, 176 stations for the 1915–2011 period, 558 stations for the  
128 1979–2011 period, and 525 stations for the 1979–2014 period. To calculate annual total  
129 precipitation, daily precipitation amounts were averaged and then multiplied by the total days of  
130 each year.

131

132 Gridded observations were developed by Livneh et al. (2013), hereafter LI2013, for the  
133 contiguous United States based on the methods of Maurer et al. (2002). Maurer et al. (2002) has  
134 been widely used in water and energy budget studies as well as climate change assessments  
135 (Wood et al. 2004; Hayhoe et al. 2004; Westerling et al. 2006; Elsner et al. 2014). LI2013 uses  
136 daily temperature and precipitation observations from approximately 20,000 NOAA Cooperative  
137 Observer (COOP) stations gridded to a spatial resolution of 1/16° latitude/longitude (~7 km).  
138 Available daily meteorological data include station-based temperature and precipitation, as well  
139 as wind from reanalysis covering the time period 1915–2011 (Livneh et al. 2013). Additional  
140 details of LI2013 can be found in Livneh et al. (2013) and Maurer et al. (2002).

141

142 Reanalysis data are from the National Centers for Environmental Prediction (NCEP) North  
143 American Regional Reanalysis (NARR; Mesinger et al. 2006). NARR combines NCEP's Eta  
144 atmospheric model and Regional Data Assimilation System to produce a dynamically consistent  
145 atmospheric and land surface hydrology dataset for North America (Mesinger et al. 2006).  
146 Compared to other reanalysis products, NARR is high resolution (~32 km) and notably

147 incorporates precipitation, a variable not typically assimilated (Mesinger et al. 2006). Further,  
148 NARR uses an updated version of the NOAA land surface model and an expanded and improved  
149 set of observations for data assimilation (Mesinger et al. 2006). NARR has been shown to have  
150 significantly improved performance relative to NCEP-Department of Energy Reanalysis 2  
151 (Mesinger et al. 2006). NARR is available at 3-hour, daily and monthly temporal resolutions for  
152 1979 to near present; we use daily means from 1979–2014. To make NARR directly comparable  
153 to gridded observations, we interpolated its native Lambert Conformal Conic grid to  $1/16^{\circ}$   
154 regular latitude using the nearest neighbor approach of MATLAB’s griddata function.

155

## 156 2.2 Methods

157 Using the three datasets described above, we assess annual and seasonal changes in total and  
158 extreme precipitation over the Northeast spanning multiple time periods, both spatially averaged  
159 and at the station/grid scale. Time periods are selected to maximize overlap across datasets and  
160 for consistency with Walsh et al. (2014). Analyses were conducted for each dataset – GHCN-D,  
161 NARR, and LI2013 – individually, and then the consistency of changes across datasets was  
162 evaluated.

163

164 Stations with long-term records are distributed unevenly in the Northeast with a higher station  
165 density near major and largely near-coastal metropolitan areas and a lower density in  
166 mountainous regions. To properly represent the regional values from station observations, we  
167 applied area averaging to calculate regional precipitation means (Groisman et al. 2004) instead of  
168 simply averaging over all stations. Area averaging is conducted by arithmetically averaging  
169 annual or seasonal precipitation values in all stations within  $1^{\circ} \times 1^{\circ}$  grid cells and then regionally

170 averaging the gridded values (Groisman et al. 2004; Walsh et al. 2014). Grid cells without any  
171 selected GHCN-D stations are treated as missing values, and therefore do not get incorporated in  
172 the regional means.

173

174 We calculate annual total precipitation by calendar year for all three daily datasets over the  
175 length of record, as well as for a few select time periods described in Section 2.1 to enable  
176 comparisons across datasets. Then, for each data point within the domain (station for station  
177 observations, grid cell for gridded observations and NARR), we calculate a linear regression  
178 from the annually averaged values, yielding an annual trend for all relevant time periods. Simple  
179 linear regression is used as the standard parametric trend analysis method with a significance test  
180 (Student's t-test) at  $p < 0.05$ . To make the trends in precipitation (absolute changes, expressed in  
181 mm decade $^{-1}$ ) more comparable among various periods, we also compute relative percent  
182 changes (expressed in % decade $^{-1}$ ) by subtracting the first point on the linear regression from the  
183 last point on the regression, and then dividing by the modeled value at the first point:

184 
$$\Delta = \frac{10 * S}{P_i} * 100\% \quad (1)$$

185 where  $\Delta$  is the relative change in precipitation (% decade $^{-1}$ ),  $S$  is the slope of the linear model  
186 (mm yr $^{-1}$ ), and  $P_i$  is the modeled precipitation value in start year  $i$  (mm). In addition to assessing  
187 linear trends in total precipitation with Student's t-test, we also conducted a rank-based Mann-  
188 Kendall significance test for annual total precipitation.

189

190 In the seasonal precipitation analyses, daily records were grouped into four seasons: spring  
191 (March, April, May), summer (June, July, August), fall (September, October, November), and  
192 winter (December, January, February). For station observations, seasonal total precipitation in  
193 each year was calculated by multiplying the daily average in a season by the total days of the  
194 season, consistent with the calculation of annual total precipitation. Because the selected stations  
195 are constrained by the 80% complete requirement in both total daily records and annual records,  
196 seasonal records were usually at least 60% complete (higher than 80% complete in most  
197 seasons). For gridded and reanalysis data, seasonal total precipitation is the sum of daily  
198 precipitation amounts in a season because both datasets provide complete daily values. The  
199 winter seasonal time series contains one less value than other seasonal series because January  
200 and February in both 2012 and 2015 fall outside the analysis periods ending in 2011 and 2014,  
201 respectively. Seasonal trends and changes in total precipitation were calculated with the same  
202 methods as annual total precipitation.

203

204 We define extreme precipitation as the amount of precipitation falling on the 1% of wet days  
205 recording the most precipitation. Specifically, for each station (for GHCN-D) or grid cell (for  
206 LI2013 and NARR), we first determined the 99<sup>th</sup> percentile threshold of daily precipitation  
207 events over each of the four periods of record (1901–2014, 1915–2011, 1979–2014, and 1979–  
208 2011). Then, for each station or grid point, we summed the total precipitation falling on days  
209 exceeding the 99<sup>th</sup> percentile threshold for each year. These annual values were then averaged by  
210 area for stations (or by grid cells for gridded observations and reanalysis) to determine the  
211 Northeast regional annual values of extreme precipitation. This procedure is consistent with  
212 Walsh et al. (2014). We repeated this process by season to calculate seasonal extreme

213 precipitation values using 32 thresholds in total for the three datasets, four periods, and four  
214 seasons. It is important to note that we calculate different 99<sup>th</sup> percentile extreme precipitation  
215 thresholds for each season. For example, the average Northeast thresholds are 38.9 mm in winter  
216 vs. 55.1 mm in summer from 1901–2014 in the GHCN-D dataset. Thus, the seasonal extreme  
217 precipitation means may appear to suggest relatively equal amounts of extreme precipitation in  
218 each season, whereas at least 75% of the 99<sup>th</sup> percentile events in the Northeast occur in summer  
219 and fall when using a single extreme threshold for the whole year (Frei et al. 2015). Thus,  
220 applying the same threshold to each season would result in small or negligible amounts of winter  
221 and spring extreme precipitation, making comparisons of gridded and reanalysis precipitation to  
222 station observations very difficult.

223

224 Trends in annual and seasonal extreme precipitation were assessed using a non-parametric,  
225 Theil-Sen robust linear regression (Theil 1950; Sen 1968). Compared to the parametric trend  
226 analysis, i.e. simple linear regression used for total precipitation, the advantages of Theil-Sen  
227 estimation is its insensitivity to outliers, making it more accurate than simple linear regression  
228 for skewed and heteroskedastic data with multiple extreme values (Alexander et al. 2006; Kunkel  
229 et al. 2010). The significance of monotonic trends ( $p < 0.05$ ) from Theil-Sen estimation is  
230 evaluated using the Mann-Kendall test (Mann 1945; Kendall 1970). After computing the trends  
231 of absolute changes (mm decade<sup>-1</sup>), relative changes in extreme precipitation (% decade<sup>-1</sup>) are  
232 also calculated with equation (1).

233

234 We note that in Section 3.1 and Tables 1–4 we use the 116 GHCN-D stations with 80% complete  
235 records from 1901–2014 and a single threshold for each station 1901–2014 to determine the 1%  
236 extreme precipitation events, which allows us to compare total and extreme precipitation  
237 amounts across four time periods. However, we use all GHCN-D stations with 80% complete  
238 records (525 stations 1979–2014, 558 stations 1979–2011, 176 stations 1915–2011) for  
239 comparison to NARR and LI2013 in Section 3.2 and Tables 5–8.

240

### 241 **3 Results and Discussion**

242 We first explore the changes in total and extreme precipitation over the length of record using  
243 station observations. Specifically, we analyze annual total and extreme precipitation and their  
244 trends (in both absolute and relative changes) across various time periods, and evaluate their  
245 spatial distributions. Seasonal total and extreme precipitation are then assessed in a similar way.  
246 Finally, we evaluate total and extreme precipitation and their seasonality in gridded observations  
247 and reanalysis data, and compare them to the station observations.

248

249 3.1 Total and extreme precipitation in station observations

250 3.1.1 Spatially averaged changes in Northeast total precipitation

251 GHCN-D annual total precipitation averaged over the Northeast region increased significantly ( $p$   
252  $< 0.05$ ) across all four time periods analyzed using linear regression with a Student's t-test and  
253 for 1979–2011 and 1979–2014 using the Mann-Kendall test (Table 1). The annual total  
254 precipitation over both 1979–2014 (1104 mm) and 1979–2011 (1104 mm) was 4.4% higher than  
255 the 1901–2014 average (1063 mm). Further, these two recent periods show much larger

256 increasing trends of 40.8 mm decade<sup>-1</sup> (4.0% decade<sup>-1</sup>) and 52.8 mm decade<sup>-1</sup> (5.2% decade<sup>-1</sup>),  
257 respectively, compared to trends over 1901–2014 (6.0 mm decade<sup>-1</sup>) and 1915–2011 (11.1 mm  
258 decade<sup>-1</sup>) (Table 1). In fact, linear trends ending in 2014 consistently increase in slope as the start  
259 date progressively moves through the 20<sup>th</sup> century (Figure 1a), confirming that linear trends in  
260 annual total precipitation in the Northeast are highly sensitive to both the start and end dates as  
261 noted in other precipitation analyses (Frei et al. 2015; Frei and Schär 2001; Wu et al. 2005).

262

263 Interestingly, when starting from 1901, the linear trend does not become significant until 2014,  
264 and the trend from 1901–2001 is -1.6 mm decade<sup>-1</sup>. Kunkel et al. (2013b) note a significant  
265 increase in total Northeast precipitation from 1901–2011, but an analysis of their data shows that  
266 there is no significant trend from 1901–2001, similar to our findings. We conclude that the shift  
267 to a wetter climate in 2002 (Figure 1b) is responsible for the significant linear trends in annual  
268 total precipitation from 1901–2014 and the progressively larger trends in recent decades (Figure  
269 1a).

270

271 A changepoint analysis using the `findchangepoints` function in MATLAB (Killick et al. 2012)  
272 identifies the abrupt shift to a wetter period in 2002 (Figure 1b). Every annual total from 2002 to  
273 2014 was above the 1901–2014 average (1063 mm), which never occurred in any previous 13-yr  
274 period. Total precipitation increased by 13% across this changepoint, with a mean from 1901–  
275 2001 of 1048 mm and from 2002–2014 of 1183 mm. There are insignificant decreasing trends  
276 both before the 2002 shift (-1.6 mm decade<sup>-1</sup> from 1901–2001) and after (-62.9 mm decade<sup>-1</sup>  
277 from 2002–2014), indicating that a changepoint analysis is preferable to a linear trend analysis to  
278 characterize the change in total precipitation from 1901–2014. Future analyses will focus on

279 identifying the dynamical changes underlying this abrupt increase in Northeast precipitation  
280 around 2001–2002.

281  
282 We attribute differences between the trends calculated in Kunkel et al. (2013b), Hayhoe et al.  
283 (2007), and this work to differences in datasets analyzed, spatial domain, data processing and  
284 quality control procedures (e.g. filling missing daily data and the spatial gridding method), and  
285 bias correction due to historical changes in instrumentation and observing practices (Legates and  
286 DeLiberty 1993; Vose et al. 2014; Menne et al. 2012a, b; Easterling et al. 1996).

287  
288 3.1.2 Spatial changes in Northeast total precipitation  
289 Shifting our focus to the spatial patterns of precipitation rates and trends over the Northeast  
290 (Figure 2), we find the expected coast-interior gradient with coastal areas generally receiving  
291 more annual total precipitation, although some mountainous stations in northern West Virginia  
292 and central New York also received very high precipitation ( $>1200 \text{ mm yr}^{-1}$ ) due to orographic  
293 effects (Kunkel et al. 2013b). Despite the substantial coast-interior gradient in total precipitation  
294 amount, total precipitation trends from 1901–2014 and 1915–2011 were generally consistently  
295 positive across the whole Northeast domain, with the exception of decreases or no significant  
296 trends in parts of West Virginia, eastern Maryland and Delaware (Figure 2b, 2c). Fifty-five of the  
297 116 stations (47%) had statistically significant positive trends from 1901–2014, whereas only 17  
298 stations (15%) from 1901–2014 had negative annual total precipitation trends, and only three of  
299 these (all in West Virginia) were statistically significant (Figure 2b). Similarly, 49% and 2% of  
300 stations experienced significant increasing and decreasing trends from 1915–2011, respectively.  
301 Relative to the longer-term period of 1901–2014, the 1979–2014 interval features a higher

302 proportion (90%) of stations with positive trends, with only 10% of the stations showing  
303 negative trends (Figure 2d). However, only 26% of the stations show positive trends that are  
304 statistically significant, although they are distributed relatively uniformly across the Northeast  
305 domain similar to the 1901–2014 trend pattern.

306

### 307 3.1.3 Spatially averaged changes in Northeast extreme precipitation

308 Recent increases in extreme precipitation over the Northeast are significantly larger than the  
309 increases in annual total precipitation described above. Annual extreme precipitation averaged  
310  $82.4 \text{ mm yr}^{-1}$  from 1901–2014, and increased significantly by  $2.4 \text{ mm decade}^{-1}$  ( $3.6\% \text{ decade}^{-1}$ )  
311 over this interval (Table 2). The positive trends in extreme precipitation ending in 2014  
312 progressively increase with later start years (Figure 3a), in parallel with the total precipitation  
313 trends. These large trends in extreme precipitation are dominated by high annual extremes since  
314 1996 (Figure 3), with the four highest extreme precipitation years in 2011 (182.8 mm), 1996  
315 (177.3 mm), 2005 (177.2 mm), and 2010 (157.9 mm). From 1996 to 2014, all but two annual  
316 extremes (1997 and 2001) are above the 1901–2014 average (Figure 3b). Similar to annual total  
317 precipitation, there is no significant trend in extreme precipitation from 1901–1995. Thus, long-  
318 term trends in extreme precipitation are likewise very sensitive to the length of records, start  
319 year, and end year.

320

321 As with total precipitation changes, changes in extreme precipitation from 1901–2014 are not  
322 well characterized by a linear trend. The changepoint algorithm identifies the 1996 jump to  
323 higher extreme precipitation that is apparent visually in the time series (Figure 3b). Averaged

324 over the Northeast, extreme precipitation from 1996–2014 was 53% higher than from 1901–  
325 1995. Interestingly, there is no significant trend within the wetter 1996–2014 interval, although  
326 the 19-year length is too short to assess trends with confidence.

327

328 Walsh et al. (2014) reported a striking extreme precipitation increase in the Northeast of 71%  
329 from 1958 to 2012, which exceeds all other regions in the continental U.S. Following the same  
330 calculation procedures as Walsh et al. (2014), we find a comparable increase (69%) in extreme  
331 precipitation relative to the 1958–2012 average. However, extreme precipitation increased only  
332 by 8.4% over the period 1958–1995, and the trend is insignificant. Therefore, we argue that the  
333 53% increase in average extreme precipitation after the 1996 changepoint is more representative  
334 of the increase in Northeast extreme precipitation.

335

### 336 3.1.4 Spatial changes in extreme precipitation

337 Figure 4a shows that, as expected, coastal areas generally received more extreme precipitation  
338 than inland areas from 1901 to 2014, which mirrors the spatial pattern in annual total  
339 precipitation. Also as in annual total precipitation, there is a pocket of elevated extreme  
340 precipitation driven by topography in northern West Virginia.

341

342 In terms of spatial patterns in the extreme precipitation trends, annual extreme precipitation  
343 increased in 58 (50%) of the 116 stations from 1901 to 2014 (Figure 4b), 30 (25%) of which  
344 were statistically significant. The stations with positive extreme precipitation trends are  
345 distributed fairly uniformly throughout the study area (Figure 4b). Only five (4.3%) stations had

346 negative trends, two of which were significant. The remaining 53 stations (45.7%) had an  
347 undetectable trend because more than half of the annual values for those stations were zero, and  
348 the Theil-Sen estimator calculates the median slope of all possible lines between any two paired  
349 points (Theil 1950; Sen 1968). This large proportion of zeroes in the station extreme  
350 precipitation time series is a result of heavy precipitation events occurring over limited time  
351 period relative to the length of record, which limits our ability to assess trend significance by  
352 station. However, this limitation does not affect the trend values themselves or the detection of  
353 spatially averaged trends as described in Section 3.1.3.

354

355 The more recent period of 1979–2014 contains a higher proportion of stations with positive  
356 trends (315 out of 525 stations, or 60%), 79 (15%) of which are statistically significant (Figure  
357 4d). Once again, the stations showing positive trends are distributed throughout the study area,  
358 with the exception of western New York State and Pennsylvania (Figure 4d) where several of the  
359 40 stations (7.6%) with decreasing trends are located. Only 3 stations (0.6%) have statistically  
360 significant decreases in extreme precipitation: Bradford Regional Airport, Pennsylvania (41.80°  
361 N, 78.64° W), Erie International Airport, Pennsylvania (42.08° N, 80.18° W), and Ashfield,  
362 Massachusetts (42.51° N, 72.85° W). Bradford and Ashfield are two of the three stations that  
363 have a significant decrease in annual total precipitation as well. Bradford Regional Airport and  
364 Erie International Airport are both located just east of Lake Erie in a local area with multiple  
365 stations reporting decreases in extreme precipitation, while Ashfield is anomalous based on  
366 surrounding stations.

367

368 Figure 5 shows the percent difference in extreme precipitation between the wetter 1996–2014  
369 period compared to 1901–1995, representing the change across the 1996 changepoint. 105 of the  
370 116 stations (91%) show higher extreme precipitation after 1996, and 56 stations exceed a 50%  
371 increase and are fairly uniformly distributed across the Northeast (Figure 5). Regions with  
372 multiple stations showing an extreme precipitation decrease across this changepoint include east  
373 of Lake Erie (western New York and Pennsylvania) and northeast West Virginia. Thus, these  
374 regions consistently show declining recent trends in total (Figure 2d) and extreme precipitation  
375 (Figures 4d and 5).

376

### 377 3.1.5 Changes in seasonal precipitation

378 Total precipitation increases in spring, summer, and fall over all four time periods of analysis  
379 (Table 3), with larger trends since 1979, consistent with the record of increasing annual total  
380 precipitation (Table 1). Over the full time period (1901–2014), only the trend in fall precipitation  
381 ( $4.8 \text{ mm decade}^{-1}$ ) is significant, while the summer trend ( $18.3 \text{ mm decade}^{-1}$ ) is significant over  
382 1979–2014 (Table 3). These findings are consistent with Kunkel et al. (2013b), who reported fall  
383 as the only season that experienced a significant increase in total precipitation 1895–2011, Frei et  
384 al. (2015), who found that precipitation during the warm season (June–October) increased after  
385 2002, and Marquardt Collow et al. (2016), who noted a significant increase in mean summer  
386 (June, July, August) precipitation over the period 1979–2014. Fall and summer precipitation  
387 experience changepoints in 2002 and 2003, respectively, suggesting that these two seasons are  
388 important drivers of the annual total precipitation changepoint in 2002. Winter precipitation, in  
389 contrast, shows a distinctly different pattern: a decreasing trend ( $-1.8 \text{ mm decade}^{-1}$ ) from 1901–  
390 2014, a near-zero trend ( $0.6 \text{ mm decade}^{-1}$ ) from 1915–2011, and large, statistically significant

391 trends ( $18.1\text{--}21.8 \text{ mm decade}^{-1}$ ) since 1979. However, the large trends since 1979 are strongly  
392 influenced by the winter 1979 value, which is the lowest in the entire record. Extending the  
393 period back just two additional years to 1977 (e.g. 1977–2014) results in lower winter trends by a  
394 factor of 2–3 that are statistically insignificant (not shown), providing further evidence of the  
395 sensitivity of trend analysis to time period analyzed.

396

397 Extreme precipitation increases across all seasons over all time periods, with the largest  
398 percentage increases in spring and winter. These increases are statistically significant for winter  
399 (all periods) and for spring over the long periods (1901–2014 and 1915–2011), as shown in  
400 Table 4. Trends are particularly large over 1979–2014 across all seasons, and seasonal  
401 contributions to the abrupt annual extreme precipitation shift in 1996 are dominated by increases  
402 in spring and fall extreme precipitation, which are 83% and 85% higher from 1996–2014 than  
403 from 1901–1995, respectively. Winter and summer extreme precipitation are 45% and 27%  
404 higher, respectively, after the 1996 shift (not shown). In addition, fall extreme precipitation  
405 contains a changepoint in 1995, one year before the annual extreme precipitation changepoint.  
406 The spring extreme precipitation changepoint occurred in 2005, but it moves to 1998 if 2003,  
407 one of the 10 lowest extreme springs on record, is removed. Thus, both fall and spring show a  
408 significant and abrupt increase in extreme precipitation in the mid-late 1990's that contributed to  
409 the annual extreme changepoint in 1996. The similar timing of the fall and spring change to  
410 wetter extreme conditions suggests that they may be driven by common dynamical changes.

411

412 3.2 Comparison of gridded and reanalysis precipitation to station observations

413 3.2.1 Spatially averaged Northeast total precipitation  
414 Overall the gridded LI2013 dataset reproduces observed station total precipitation and its trends  
415 well. The annual total precipitation during 1915–2011 and 1979–2011 in LI2013 are 1088 and  
416 1143 mm, respectively, compared to 1071 and 1110 mm for the same periods in GHCN-D  
417 (Table 5). The 1979–2011 annual precipitation trend in LI2013 ( $54.2 \text{ mm decade}^{-1}$ ) is slightly  
418 lower than the trend in GHCN-D ( $56.8 \text{ mm decade}^{-1}$ ), while the trend during 1915–2011 (12.4  
419  $\text{mm decade}^{-1}$ ) is slightly higher than the GHCN-D trend ( $10.7 \text{ mm decade}^{-1}$ ). Additionally,  
420 consistent with GHCN-D, trends in LI2013 significantly increase from 1915–2011 using linear  
421 regression with a Student's t-test and from 1979–2011 using linear regression with a Student's t-  
422 test and the Mann-Kendall test. The changepoint algorithm identifies a significant shift to wetter  
423 conditions in the LI2013 dataset in 2003, only one year later than the changepoint in the GHCN-  
424 D data. Figure 6a shows that LI2013 also closely reproduces the spatial distribution of annual  
425 total precipitation observed at GHCN-D stations from 1915–2011. LI2013 also reasonably  
426 captures GHCN-D total precipitation trends, although there are differences, such as LI2013  
427 containing a drying trend in western Maine compared to a significant wetting trend in GHCN-D  
428 (Figure 6b).

429  
430 NARR annual total precipitation for 1979–2014 is 1041 mm, compared to 1111 mm in GHCN-D  
431 for the same period. With an underestimation of 6.3%, this difference is larger than that found  
432 between LI2013 and GHCN-D. In contrast to significant trends in GHCN-D, trends in NARR  
433 annual precipitation are insignificant in both periods analyzed (1979–2014 and 1979–2011), and  
434 are a remarkable 2–9 times lower than the GHCN-D trends (Table 5). Furthermore, the  
435 changepoint analysis identifies no significant changepoints in the NARR annual total

436 precipitation time series. Spatially, Figure 6c shows that while NARR generally captures the  
437 lower annual precipitation values at inland GHCN-D stations, NARR tends to underestimate  
438 annual precipitation at other GHCN-D stations. More notable, however, is that NARR has  
439 decreasing total precipitation trends in many areas over the period 1979–2014, particularly along  
440 the coast and in western Pennsylvania, New York, and West Virginia (Figure 6d). In contrast,  
441 GHCN-D has positive trends consistently across most stations in the domain.

442

443 We note a few attributes of the source data and development of GHCN-D, LI2013, and NARR  
444 that are likely responsible for their disagreement. Although GHCN-D and LI2013 are developed  
445 from original observations of COOP stations, LI2013 uses far more stations (about 20,000) with  
446 less strict completeness criterion (at least 20 years of valid data) through the contiguous U.S.  
447 compared to our 176 GHCN-D stations in the Northeast fulfilling the 80% completeness  
448 threshold from 1915–2011 (Livneh et al. 2013; Menne et al. 2012a, b). Precipitation data in the  
449 LI2013 dataset is also linearly apportioned among days based on the time of observation to very  
450 fine spatial resolution ( $1/16^\circ$ ) and subsequently scaled on a monthly basis so as to match the  
451 long-term mean (Livneh et al. 2013), which the authors caution may make the data unsuitable for  
452 trend analysis (Livneh et al. 2015). However, we find that despite monthly scaling, LI2013  
453 trends closely match the GHCN-D trends in annual total precipitation.

454

455 We note two relevant challenges with NARR. The first is that some discontinuities exist along  
456 the U.S.–Canada border (Luo et al. 2007; Milrad et al. 2012). These discontinuities can be  
457 attributed to characteristics of the two different national observational datasets, in particular the  
458 different spatial density of assimilated rain gauges, merged by NCEP, and the fact that no

459 smoothing was applied when these two datasets were merged (Mo et al. 2005; Luo et al. 2007;  
460 Milrad et al. 2012). To lessen the effects of this discontinuity in our analyses, we masked out a  
461 buffer of cells along the U.S.–Canada border. The second challenge is the sharp precipitation  
462 gradients along the coastline. Due to lack of station observations, the merged precipitation  
463 dataset from the Climate Prediction Center in NCEP is known to be increasingly less reliable  
464 over the oceans north of 42.5°N (Mesinger et al. 2006). Thus, NARR is meant to be primarily  
465 used over land and may be inaccurate over northern oceans (Mesinger et al. 2006; Bukovsky and  
466 Karoly 2007). This provides a likely explanation as to why NARR grids near coastlines,  
467 incorporating some information from ocean grid points, have lower precipitation relative to  
468 GHCN-D stations.

469

#### 470 3.2.2 Spatially averaged Northeast extreme precipitation

471 LI2013 reproduces the regional average extreme precipitation, but LI2013 extreme precipitation  
472 trends differ from the GHCN-D trends (Table 6), contrary to the ability of LI2013 to capture  
473 annual total precipitation trends as noted above. Specifically, the trends in extreme precipitation  
474 during 1915–2011 and 1979–2011 in LI2013 are lower than GHCN-D, and unlike GHCN-D,  
475 they are not statistically significant, nor do they have a statistically significant changepoint.  
476 LI2013 reproduces well the GHCN-D spatial pattern of extreme precipitation amount (Figure  
477 7a), but the 1915–2011 LI2013 trends, both positive and negative, are substantially larger over  
478 many regions than the GHCN-D trends (Figure 7b).

479

480 Like annual total precipitation, NARR also tends to underestimate extreme precipitation (Table  
481 6). The 1979–2011 annual extreme precipitation in NARR (77.5 mm) is 9.9% lower than in  
482 GHCN-D (86 mm). While the NARR trend in 1979–2014 annual extreme precipitation (4.9 mm  
483 decade<sup>-1</sup>) is insignificant and much lower than the GHCN-D trend (12.6 mm decade<sup>-1</sup>), the  
484 NARR trend (15.8 mm decade<sup>-1</sup>) is similar to the GHCN-D trend (14.7 mm decade<sup>-1</sup>) if the  
485 analysis is restricted to 1979–2011. The differences mainly derive from anomalously low  
486 extreme precipitation in NARR for 2013–2014; approximately 45% lower than the 1979–2014  
487 average NARR extreme precipitation (77.5 mm). In contrast, the 2013–2014 extreme  
488 precipitation in GHCN-D is almost equal to its 1979–2014 average. In further contrast with the  
489 GHCN-D data, the NARR extreme precipitation time series has no significant changepoints.  
490 Spatially, Figure 7c shows a widespread underestimation of average extreme precipitation by  
491 NARR relative to GHCN-D from 1979–2014. NARR does capture GHCN-D trends in extreme  
492 precipitation from 1979–2014 in several regions, including central and western New York,  
493 western Maine, Delaware, western West Virginia, and southern New Jersey, but otherwise shows  
494 significant differences from GHCN-D spatial trends. These spatial differences are largest in New  
495 Hampshire, Massachusetts, Vermont, Connecticut and Rhode Island (Figure 7d).

496

### 497 3.2.3 Seasonal precipitation

498 Relative to GHCN-D, LI2013 slightly overestimates seasonal total precipitation while NARR  
499 underestimates seasonal total precipitation (Table 7). Low seasonal total precipitation values in  
500 NARR are consistent with the low annual total values in NARR noted in section 3.2.1.

501

502 LI2013 seasonal total precipitation trends are similar to GHCN-D trends, whereas trends in  
503 NARR are lower than those in GHCN-D. Of the five significant seasonal trends in GHCN-D,  
504 two occur during time periods that overlap with LI2013 (1915–2011 fall and 1979–2011 winter),  
505 and LI2013 is also significant for both. However, there are three significant trends in GHCN-D  
506 for time periods that NARR is available, and NARR matches with 1979–2011 winter only,  
507 although it still underestimates the value ( $15.9 \text{ mm decade}^{-1}$  for NARR compared to  $20.1 \text{ mm}$   
508  $\text{decade}^{-1}$  for GHCN-D).

509

510 For seasonal extreme precipitation (Table 8), once again LI2013 averages are very close to  
511 GHCN-D seasonal extreme precipitation averages, whereas NARR generally underestimates  
512 seasonal extreme precipitation, with the biggest differences in summer (15%) and smallest  
513 differences in winter (0.6%). The seasonal extreme precipitation trends of LI2013 are equal to or  
514 smaller than those from GHCN-D, however LI2013 fails to capture most significant seasonal  
515 trends in GHCN-D (except winter 1979–2011). NARR seasonal extreme precipitation trends are,  
516 similar to seasonal total precipitation trends, equal to or smaller than GHCN-D trends in most  
517 cases with the exceptions of spring and fall 1979–2011. Of the four significant positive trends in  
518 GHCN-D seasonal extreme precipitation that occur in time periods for which NARR data is  
519 available, NARR is significant for two of them, spring and winter 1979–2011.

520

521

522

523

524 **4 Conclusions**

525 Over the 1901–2014 station observational record in the Northeast, we find a significant 6.8%  
526 ( $0.6\% \text{ decade}^{-1}$ ) increase in annual total precipitation and a much larger 41% ( $3.6\% \text{ decade}^{-1}$ )  
527 increase in annual extreme precipitation. However, a key conclusion of our study is that the  
528 recent increases in annual total and extreme precipitation in the Northeast are best characterized  
529 as abrupt shifts in 2002 and 1996, respectively, rather than long-term increases over several  
530 decades as could be implied from a linear trend. While the pre-changepoint trends in annual total  
531 (1901–2001;  $-1.6 \text{ mm decade}^{-1}$ ) and annual extreme (1901–1995;  $0.1 \text{ mm decade}^{-1}$ ) precipitation  
532 are not statistically significant, total precipitation from 2002–2014 was 13% higher than from  
533 1901–2001 and extreme precipitation from 1996–2014 was 53% higher than from 1901–1995,  
534 with both increases being statistically significant. The fact that these wetter periods both abut the  
535 end of our record in 2014 means that any long-term linear trends are highly dependent on their  
536 start date, and should therefore be interpreted with caution, particularly when extrapolating into  
537 the future. Of note, the recent 2015–2016 drought in the Northeast is not included in our  
538 analyses, although it is not likely to change the significance of the post-changepoint increases.

539

540 Spatially, we find that the increases in annual total and extreme precipitation are widespread  
541 across the Northeast domain, with the exception of smaller increases and even some significant  
542 decreases to the east of Lake Erie, and in the southern part of the domain in West Virginia,  
543 Maryland, and Delaware. Our seasonal analysis reveals that fall and summer total precipitation  
544 have statistically significant increases after changepoints in 2002 and 2003, respectively,  
545 suggesting that they contribute to the annual total precipitation changepoint in 2002. The extreme  
546 precipitation increase across the 1996 changepoint is associated with 83% and 85% increases in

547 spring and fall extreme precipitation, respectively, and may indicate common atmospheric  
548 forcing of spring and fall extreme precipitation in the mid-late 1990's. The increase in fall  
549 precipitation across the 1995 changepoint is consistent with Kunkel et al.'s (2010) finding that  
550 increased heavy precipitation associated with tropical cyclones after 1994 is an important driver  
551 of the overall increase in extreme precipitation. Our ongoing investigations into the underlying  
552 dynamical causes for Northeast annual total and extreme precipitation increases are focusing on  
553 these critical time periods in the late 1990s and early 2000s.

554

555 Our comparison of spatial and temporal extreme precipitation patterns in station (GHCN-D),  
556 gridded (LI2013), and reanalysis (NARR) datasets shows that LI2013 is more consistent with  
557 station data than NARR. LI2013 reasonably captures the mean (within 2%) and seasonality  
558 (overestimates by 0–10%) of GHCN-D extreme precipitation, but contains significant  
559 differences in its trends. NARR underestimates regionally averaged extreme precipitation across  
560 all seasons by 0.6–15%, and the annual extreme trends show significant differences in their  
561 spatial distribution, particularly over New England. Perhaps more importantly, both the NARR  
562 and LI2013 annual extreme time series have no significant changepoints.

563

564 LI2013 does, however, reproduce GHCN-D regionally averaged annual and seasonal total  
565 precipitation within 5% (and usually within 3%), and its trends faithfully capture those from  
566 station observations both across the region and averaged over the Northeast. In addition, LI2013  
567 has a changepoint in 2003, only one year later than the changepoint identified in GHCN-D  
568 annual total precipitation. However, NARR underestimates annual and seasonal total  
569 precipitation by 3–10%, and has annual total precipitation trends that are a factor of 2–9 times

570 smaller than GHCN-D trends. Spatially, NARR is also less accurate than LI2013, with  
571 decreasing 1979–2014 trends over much of the coastal and western portions of the domain where  
572 GHCN-D trends are positive. This comparison of LI2013 and NARR to GHCN-D provides  
573 important information on the strengths and limitations of these products for use in analyzing  
574 hydroclimate, forcing climate impacts models, and identifying drivers of total and extreme  
575 precipitation.

576

## 577 **Acknowledgments**

578 Station observation, gridded observation, and reanalysis data are available at  
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585

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- 696
- 697 **Tables**
- 698 Table 1: Means and trends of GHCN-D annual total precipitation. The trends are calculated from simple linear  
 699 regression. The symbols, \* and #, denote the trend is significant at 0.05 level using parametric method (t-test) and  
 700 nonparametric method (Mann-Kendall test), respectively. Percentage trends are calculated by dividing the linearly  
 701 modeled change per decade by the value of the start year.

	Units	1901–2014	1915–2011	1979–2014	1979–2011
Mean	mm yr <sup>-1</sup>	1063	1059	1104	1104
Trend	mm decade <sup>-1</sup>	6.0*	11.1*	40.8**#	52.8**#
Trend	% decade <sup>-1</sup>	0.6	1.1	4.0	5.2

702

703 Table 2: Means and trends of annual extreme precipitation in GHCN-D dataset. The trends are calculated from  
 704 Theil-Sen robust linear regression. A # denotes the trend is significant at 0.05 level using Mann-Kendall test.  
 705 Percentage trends are calculated by dividing the linearly modeled change per decade by the value of the start year.

	Units	1901–2014	1915–2011	1979–2014	1979–2011
Mean	mm yr <sup>-1</sup>	82.4	83.0	97.4	97.3
Trend	mm decade <sup>-1</sup>	2.4#	3.1#	13.9#	19.7#
Trend	% decade <sup>-1</sup>	3.6	4.6	19.2	30.3

706  
707

708

709  
 710 Table 3: Means and trends of GHCN-D seasonal total precipitation. The trends are calculated from simple linear  
 711 regression. The symbols, \* and #, denote the trend is significant at 0.05 level using parametric method (t-test) and  
 712 nonparametric method (Mann-Kendall test), respectively. Percentage trends are calculated by dividing the linearly  
 713 modeled change per decade by the value of the start year.

	Units	1901–2014	1915–2011	1979–2014	1979–2011
<b>Spring</b>					
Mean	mm yr <sup>-1</sup>	267.3	265.7	278.1	279.6
Trend	mm decade <sup>-1</sup>	0.9	3.0	4.4	8.6
Trend	% decade <sup>-1</sup>	0.4	1.2	1.6	3.2
<b>Summer</b>					
Mean	mm yr <sup>-1</sup>	302.4	299.7	313.0	309.4
Trend	mm decade <sup>-1</sup>	0.9	1.6	18.3*#	16.6
Trend	% decade <sup>-1</sup>	0.3	0.5	6.5	5.9
<b>Fall</b>					
Mean	mm yr <sup>-1</sup>	262.3	265.4	285.2	287.9
Trend	mm decade <sup>-1</sup>	4.8*#	6.0*#	6.8	14.5
Trend	% decade <sup>-1</sup>	2.1	2.5	2.5	5.5
<b>Winter</b>					
Mean	mm yr <sup>-1</sup>	233.9	229.0	226.0	225.0
Trend	mm decade <sup>-1</sup>	-1.8	0.6	18.1*#	21.8*#
Trend	% decade <sup>-1</sup>	-0.7	0.3	9.3	11.5

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715 Table 4: Means and trends of GHCN-D seasonal extreme precipitation. The trends are calculated from Theil-Sen  
 716 robust linear regression. A # denotes the trend is significant at 0.05 level using Mann-Kendall test. Percentage trends  
 717 are calculated by dividing the linearly modeled change per decade by the value of the start year.

	Units	1901–2014	1915–2011	1979–2014	1979–2011
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<b>Spring</b>					
Mean	mm yr <sup>-1</sup>	18.1	17.7	25.1	24.6
Trend	mm decade <sup>-1</sup>	0.8 <sup>#</sup>	1.2 <sup>#</sup>	4.1	4.4
Trend	% decade <sup>-1</sup>	6.4	10.2	23.2	25.0
<b>Summer</b>					
Mean	mm yr <sup>-1</sup>	22.9	23.0	25.0	24.8
Trend	mm decade <sup>-1</sup>	0.2	0.1	2.5	2.4
Trend	% decade <sup>-1</sup>	0.9	0.6	12.4	11.8
<b>Fall</b>					
Mean	mm yr <sup>-1</sup>	21	21.8	26.7	27.1
Trend	mm decade <sup>-1</sup>	0.6	0.8	3.5	5.3
Trend	% decade <sup>-1</sup>	3.4	4.8	17.1	28.8
<b>Winter</b>					
Mean	mm yr <sup>-1</sup>	15.1	15.0	17.3	17.4
Trend	mm decade <sup>-1</sup>	0.5 <sup>#</sup>	0.9 <sup>#</sup>	3.8 <sup>#</sup>	5.3 <sup>#</sup>
Trend	% decade <sup>-1</sup>	4.3	8.3	35.3	57.5

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719 Table 5: Means and trends of GHCN-D, LI2013, and NARR annual total precipitation. An x denotes a combination  
 720 of time period and dataset that is not available. The trends are calculated from simple linear regression. The  
 721 symbols, \* and #, denote the trend is significant at 0.05 level using parametric method (t-test) and nonparametric  
 722 method (Mann-Kendall test), respectively.

	Units	1901–2014	1915–2011	1979–2014	1979–2011
<b>Mean</b>					
GHCN-D	mm yr <sup>-1</sup>	1063	1071	1111	1110
LI2013	mm yr <sup>-1</sup>	x	1088	x	1143
NARR	mm yr <sup>-1</sup>	x	x	1041	1052
<b>Trend</b>					
GHCN-D	mm decade <sup>-1</sup>	6.0*	10.7*	46.4**#	56.8**#
LI2013	mm decade <sup>-1</sup>	x	12.4**#	x	54.2**#
NARR	mm decade <sup>-1</sup>	x	x	5.4	25.9

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724 Table 6: Means and trends of GHCN-D, LI2013, and NARR annual extreme precipitation. An x denotes a  
 725 combination of time period and dataset that is not available. The trends are calculated from Theil-Sen robust linear  
 726 regression. A # denotes the trend is significant at 0.05 level using Mann-Kendall test.

	Units	1901–2014	1915–2011	1979–2014	1979–2011
<b>Mean</b>					
GHCN-D	mm yr <sup>-1</sup>	82.4	82.3	86.0	85.6
LI2013	mm yr <sup>-1</sup>	x	83.9	x	85.1
NARR	mm yr <sup>-1</sup>	x	x	77.5	77.9
<b>Trend</b>					
GHCN-D	mm decade <sup>-1</sup>	2.4 <sup>#</sup>	2.3 <sup>#</sup>	12.6 <sup>#</sup>	14.7 <sup>#</sup>
LI2013	mm decade <sup>-1</sup>	x	1.3	x	12
NARR	mm decade <sup>-1</sup>	x	x	4.9	15.8 <sup>#</sup>

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735 Table 7: Means and trends of GHCN-D, LI2013, and NARR seasonal total precipitation. An x denotes a  
 736 combination of time period and dataset that is not available. The trends are calculated from simple linear regression.  
 737 The symbols, \* and #, denote the trend is significant at 0.05 level using parametric method (t-test) and  
 738 nonparametric method (Mann-Kendall test), respectively.

	Units	1901–2014	1915–2011	1979–2014	1979–2011
<b>Spring Mean</b>					
GHCN-D	mm yr <sup>-1</sup>	267.3	262.7	282.4	283.6
LI2013	mm yr <sup>-1</sup>	x	273	x	290.5
NARR	mm yr <sup>-1</sup>	x	x	272.8	277.3
<b>Spring Trend</b>					
GHCN-D	mm decade <sup>-1</sup>	0.9	2.6	7.0	11.1
LI2013	mm decade <sup>-1</sup>	x	3.6*	x	9.2
NARR	mm decade <sup>-1</sup>	x	x	4.1	-2.8
<b>Summer Mean</b>					
GHCN-D	mm yr <sup>-1</sup>	302.4	299.6	309.8	307.1
LI2013	mm yr <sup>-1</sup>	x	302.5	x	315
NARR	mm yr <sup>-1</sup>	x	x	279.5	281.2
<b>Summer Trend</b>					
GHCN-D	mm decade <sup>-1</sup>	0.9	1.8	17.0*#	16.3
LI2013	mm decade <sup>-1</sup>	x	2.1	x	16
NARR	mm decade <sup>-1</sup>	x	x	2.9	7.4
<b>Fall Mean</b>					
GHCN-D	mm yr <sup>-1</sup>	262.3	268.3	285.2	286.9
LI2013	mm yr <sup>-1</sup>	x	272.6	x	296.8
NARR	mm yr <sup>-1</sup>	x	x	261.5	265.2
<b>Fall Trend</b>					
GHCN-D	mm decade <sup>-1</sup>	4.8*#	5.9*#	9.9	16.4
LI2013	mm decade <sup>-1</sup>	x	5.9*#	x	15.5
NARR	mm decade <sup>-1</sup>	x	x	-1	5.7
<b>Winter Mean</b>					
GHCN-D	mm yr <sup>-1</sup>	233.9	228.6	231.5	230.1
LI2013	mm yr <sup>-1</sup>	x	239.2	x	236.5
NARR	mm yr <sup>-1</sup>	x	x	223.4	223.1
<b>Winter Trend</b>					

GHCN-D	mm decade <sup>-1</sup>	-1.8	0.1	17.7*#	20.1*#
LI2013	mm decade <sup>-1</sup>	x	1.2	x	20.3*#
NARR	mm decade <sup>-1</sup>	x	x	11.5	15.9*#

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744 Table 8: Means and trends of GHCN-D, LI2013, and NARR seasonal extreme precipitation. An x denotes a  
 745 combination of time period and dataset that is not available. The trends are calculated from Theil-Sen robust linear  
 746 regression. A # denotes the trend is significant at 0.05 level using Mann-Kendall test.

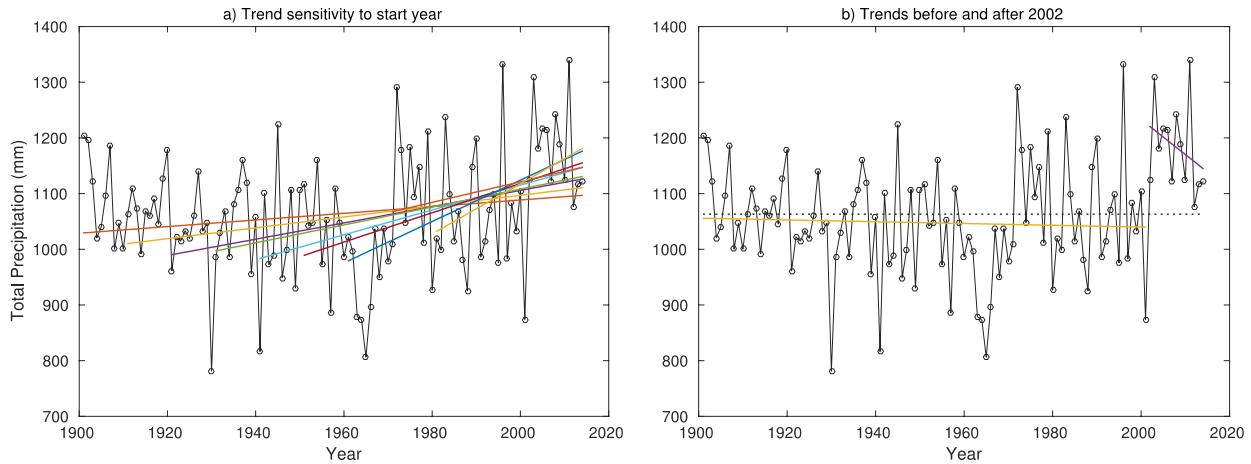
	Units	1901–2014	1915–2011	1979–2014	1979–2011
<b>Spring Mean</b>					
GHCN-D	mm yr <sup>-1</sup>	18.1	17.1	19.2	19.0
LI2013	mm yr <sup>-1</sup>	x	18.7	x	19.1
NARR	mm yr <sup>-1</sup>	x	x	18.4	18.6
<b>Spring Trend</b>					
GHCN-D	mm decade <sup>-1</sup>	0.9*	0.8*	3.8*	3.7*
LI2013	mm decade <sup>-1</sup>	x	0.6	x	2.5
NARR	mm decade <sup>-1</sup>	x	x	2.6	4.7*
<b>Summer Mean</b>					
GHCN-D	mm yr <sup>-1</sup>	22.9	22.5	23.3	23.0
LI2013	mm yr <sup>-1</sup>	x	23.5	x	22.9
NARR	mm yr <sup>-1</sup>	x	x	19.7	19.6
<b>Summer Trend</b>					
GHCN-D	mm decade <sup>-1</sup>	0.2	0.2	2.9*	2.8
LI2013	mm decade <sup>-1</sup>	x	-0.1	x	1.8
NARR	mm decade <sup>-1</sup>	x	x	2.2	2.7
<b>Fall Mean</b>					
GHCN-D	mm yr <sup>-1</sup>	21	21.6	22.7	22.7
LI2013	mm yr <sup>-1</sup>	x	22.2	x	22.9
NARR	mm yr <sup>-1</sup>	x	x	20.0	20.2
<b>Fall Trend</b>					
GHCN-D	mm decade <sup>-1</sup>	0.6	0.6	3.3	4.8
LI2013	mm decade <sup>-1</sup>	x	0.2	x	4.8
NARR	mm decade <sup>-1</sup>	x	x	1.7	5.0
<b>Winter Mean</b>					
GHCN-D	mm yr <sup>-1</sup>	15.1	15.1	16.1	16.1
LI2013	mm yr <sup>-1</sup>	x	16.7	x	16.1
NARR	mm yr <sup>-1</sup>	x	x	16.0	16.0
<b>Winter Trend</b>					
GHCN-D	mm decade <sup>-1</sup>	0.5*	0.8*	3.2	4.4*
LI2013	mm decade <sup>-1</sup>	x	0.3	x	4.0*
NARR	mm decade <sup>-1</sup>	x	x	2.4	4.4*

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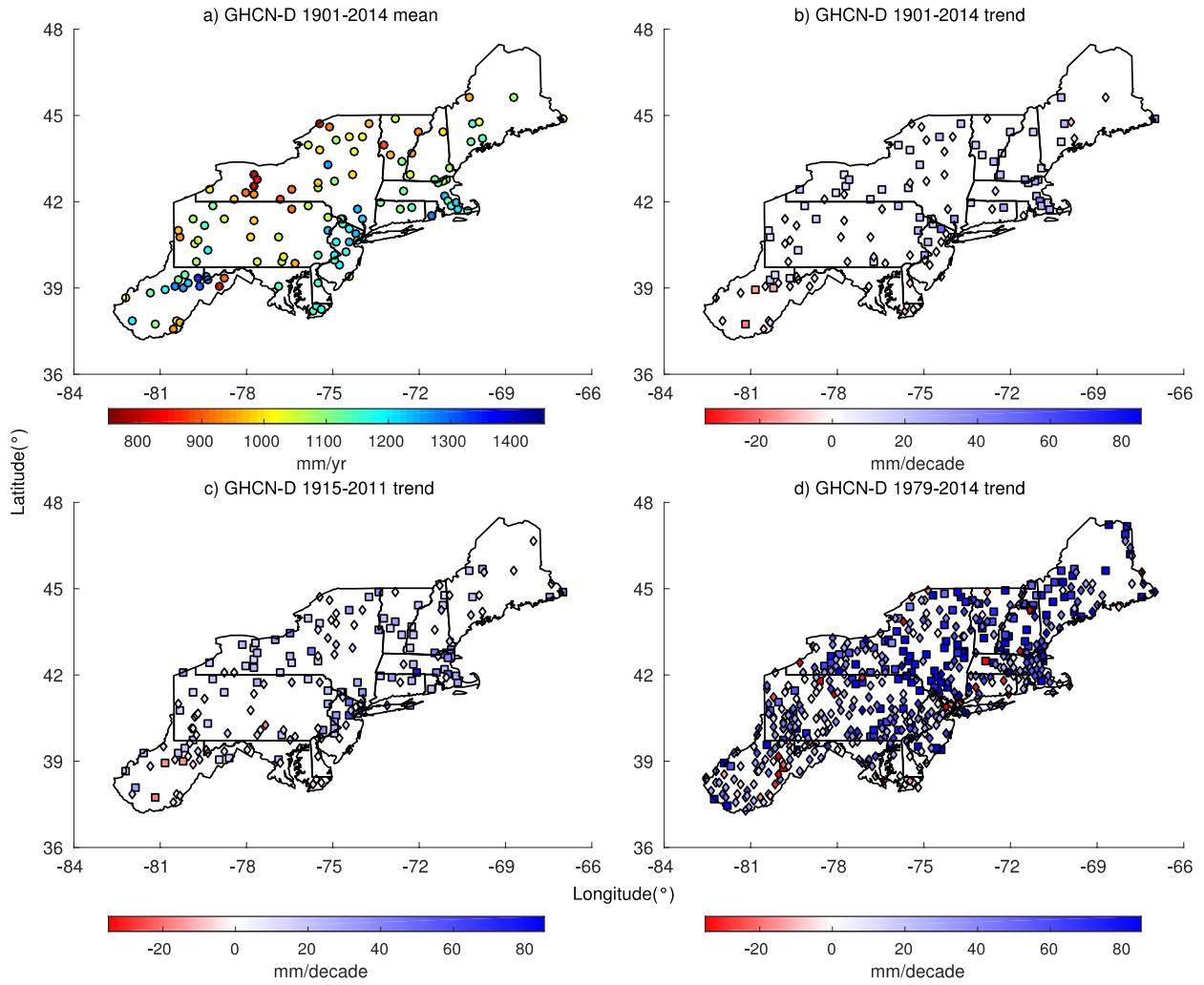
749 **Figure Caption List**

750 Figure 1: Time series of spatially averaged Northeast GHCN-D annual total precipitation from 751 1901–2014 with (a) nine trendlines for time periods starting in 1901, 1911, 1921, 1931, 752 1941, 1951, 1961, 1971, and 1981, and ending in 2014; and (b) dashed line denoting 1901– 753 2014 average annual total precipitation and trendlines before and after the changepoint year 754 of 2002.....	35
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758 Figure 3: Time series of spatially averaged Northeast GHCN-D annual extreme precipitation 759 from 1901–2014 with (a) nine trendlines for time periods starting in 1901, 1911, 1921, 1931, 760 1941, 1951, 1961, 1971, and 1981, and ending in 2014; and (b) dashed line denoting 1901– 761 2014 average annual extreme precipitation and trendlines before and after the changepoint 762 year of 1996. ....	37
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767 Figure 5: Percentage change in annual extreme precipitation between the periods 1996–2014 and 768 1901–1995 relative to 1901–1995. ....	39
769 Figure 6: LI2013 (shading) and GHCN-D (points) annual total precipitation (a) means and (b) 770 trends 1915–2011. NARR (shading) and GHCN-D (points) annual total precipitation (c) 771 means and (d) trends 1979–2014. In (b) and (d), square points represent significant trends 772 while diamond points represent insignificant trends. ....	40
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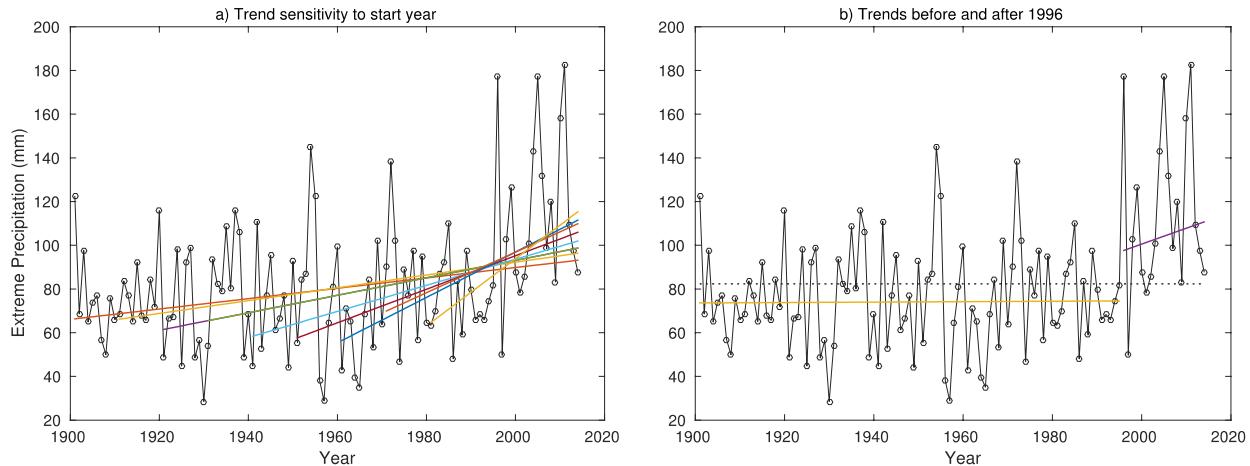


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788 changepoint year of 2002.

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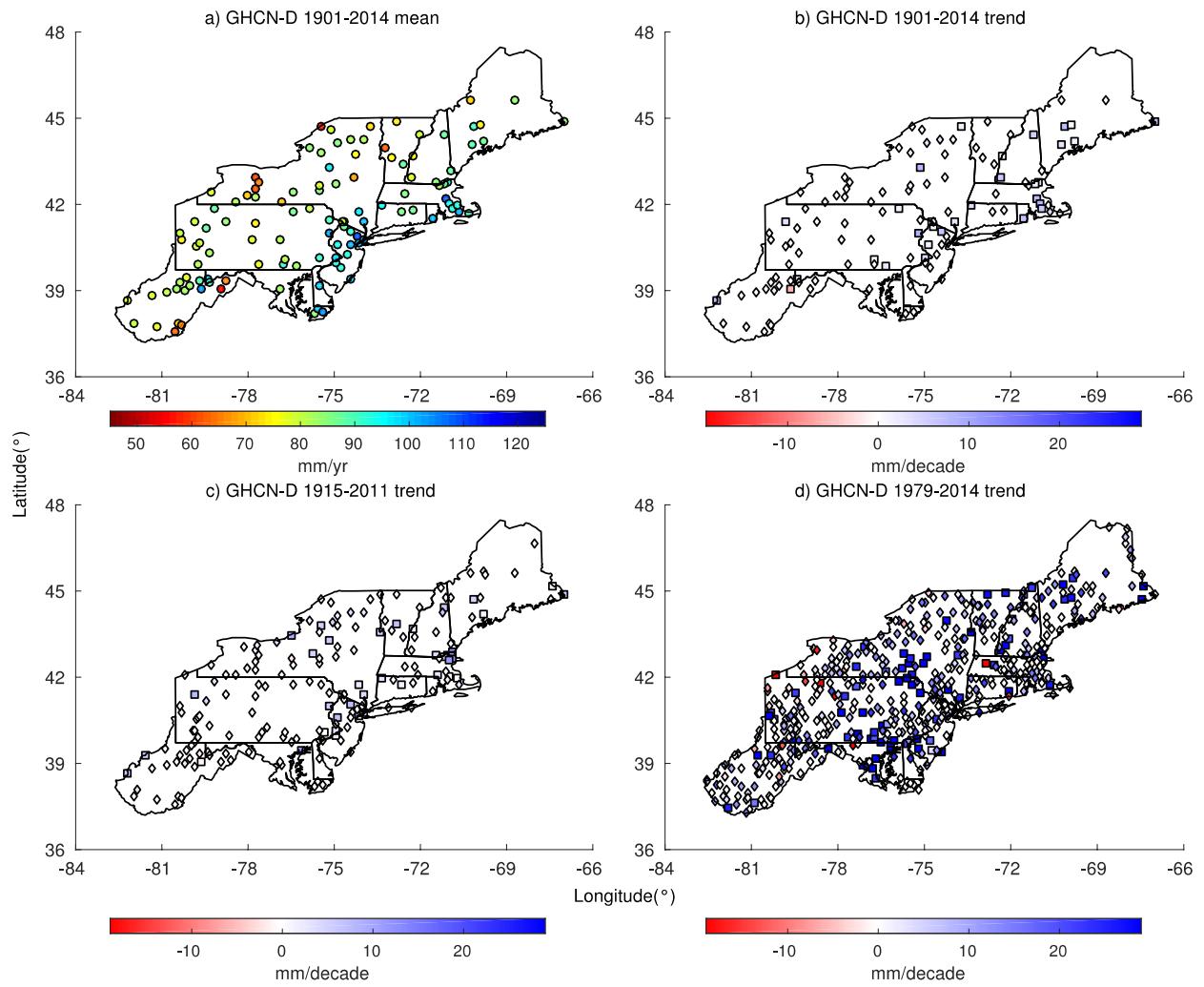
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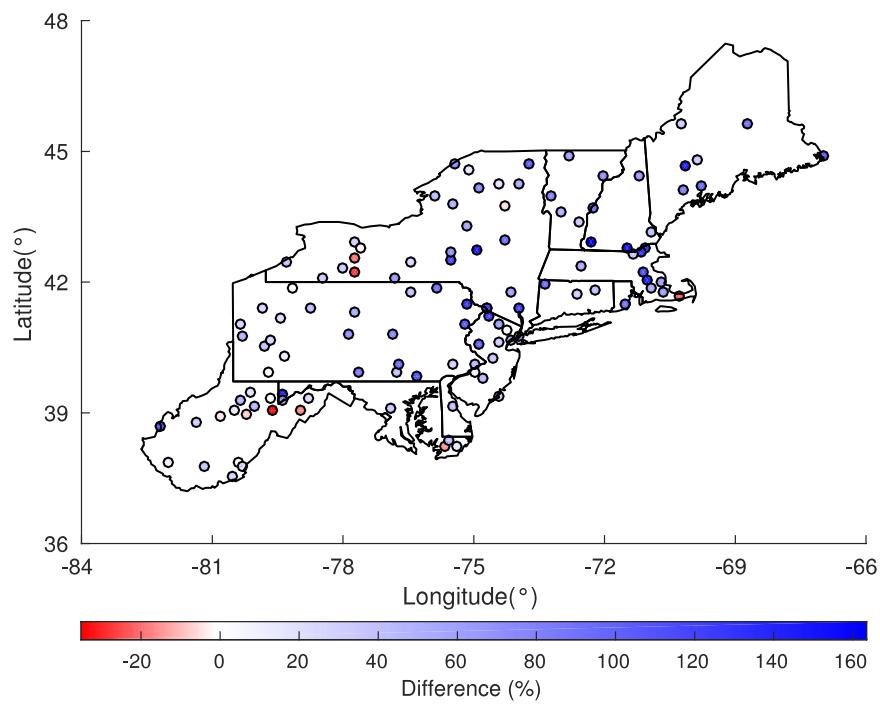
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 797 ending in 2014; and (b) dashed line denoting 1901–2014 average annual extreme precipitation and trendlines before  
 798 and after the changepoint year of 1996.

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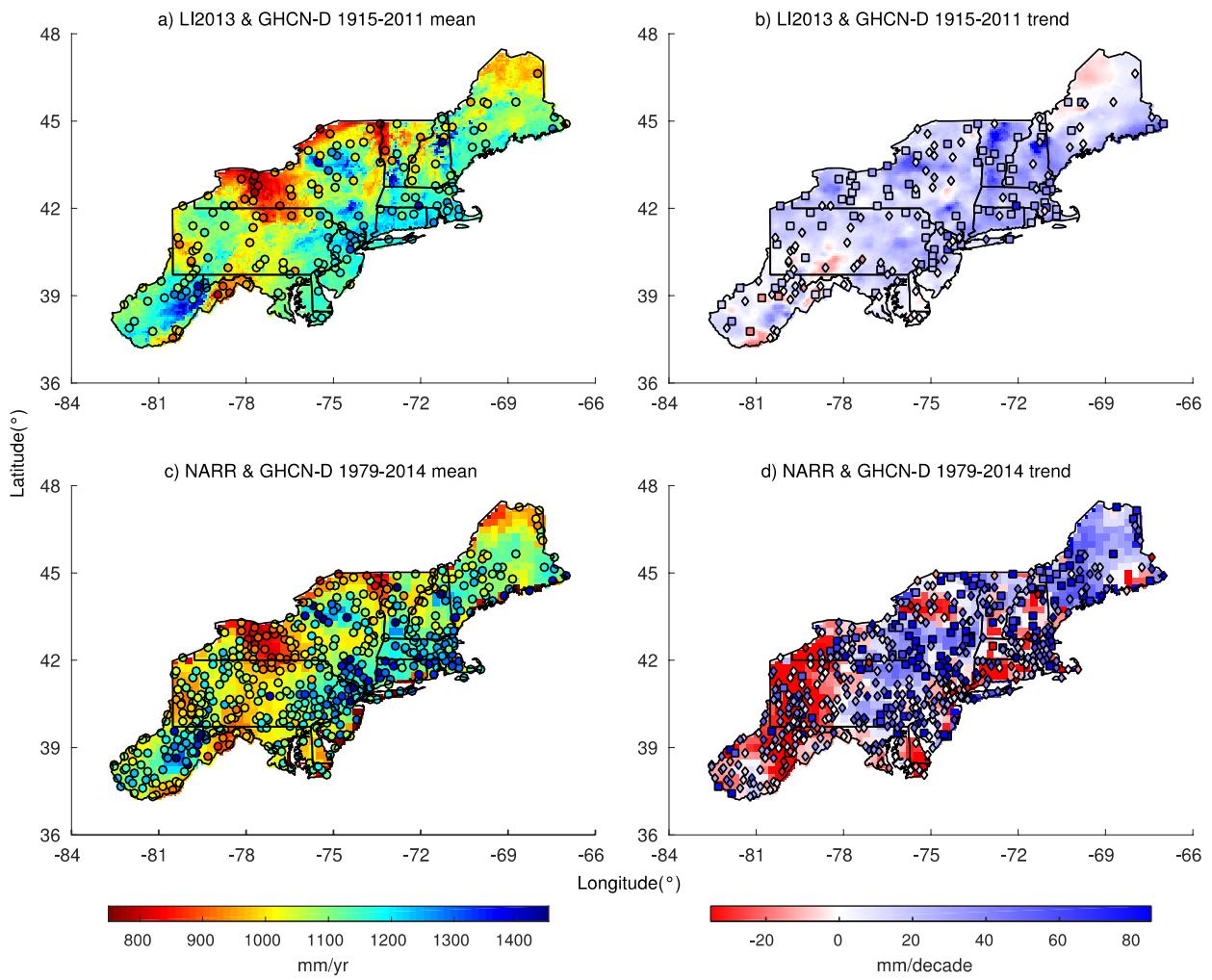
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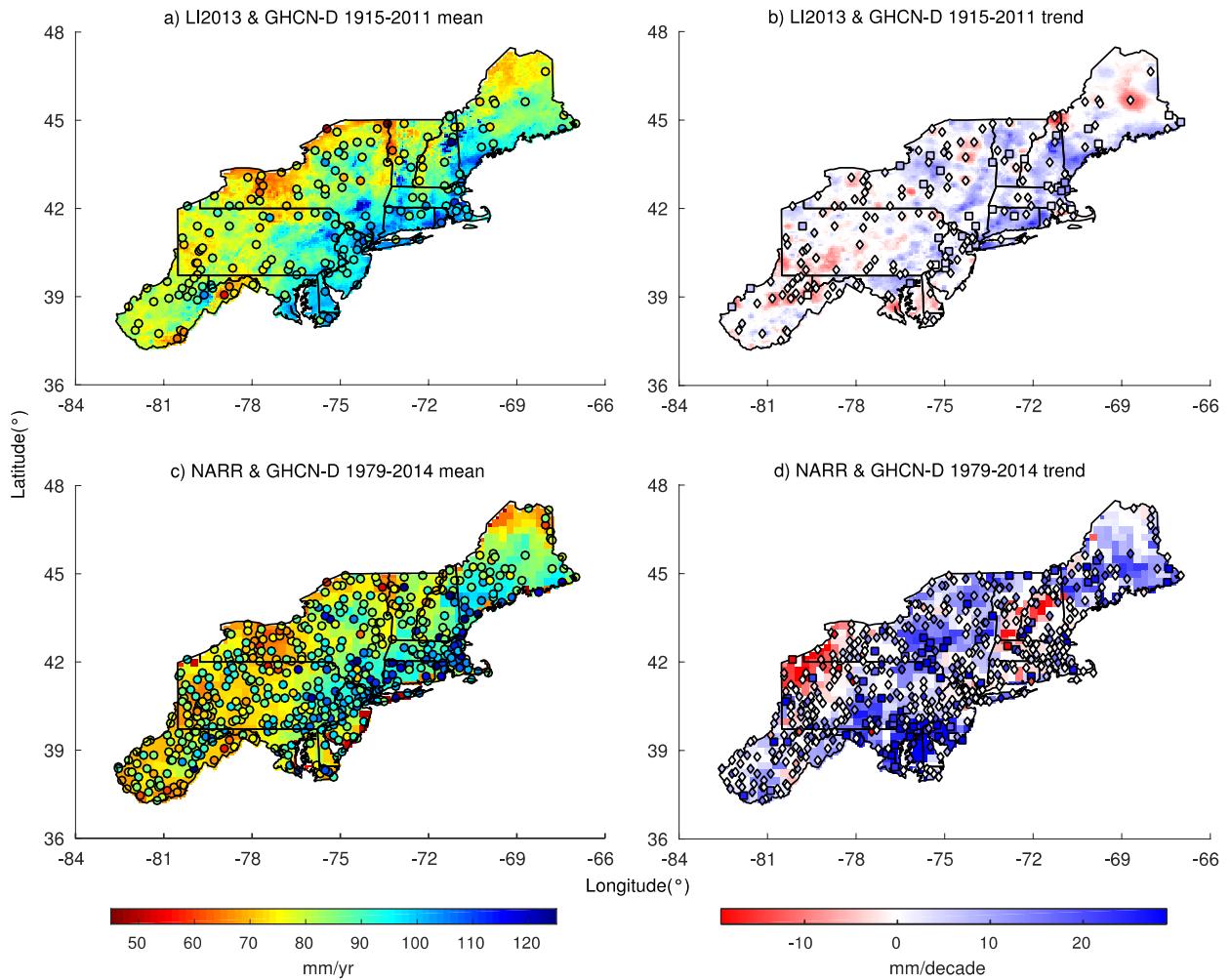
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826 Figure 6: LI2013 (shading) and GHCN-D (points) annual total precipitation (a) means and (b) trends 1915–2011.

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828 NARR (shading) and GHCN-D (points) annual total precipitation (c) means and (d) trends 1979–2014. In (b) and

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 839 and (d), square points represent significant trends, diamond points represent insignificant trends, and white points  
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